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CONSTRUCTION MATERIALS OF ACTIVE ZONES OF NEW GENERATION NUCLEAR REACTORS

The materials of the article consider the analysis of construction materials of active zones of new generation nuclear reactors. The analysis reflects general ideas about the development of reactor technologies: in the 1950s and 1960s, the first generation of reactors was created; in the early 1970s, the operation of industrial reactors began - reactors of the second generation: pressurized water reactors (WWER, PWR), boiling water reactors (RBMK, BWR), heavy water reactors (CANDU), as well as gas-cooled reactors (AGR). Further development of some types of reactors made it possible to create reactors of the third generation in the 1980s. Priority when choosing directions of development in the category of revolutionary projects should have proposals capable of bringing a new quality to solving the problems of the nuclear energy industry of the future. Promising reactors have advantages in economy, safety, reliability and non-proliferation of nuclear materials. The effectiveness and reliability of structural materials are determined by the totality of changes in the characteristics of the materials as a result of the entire complex of phenomena occurring in them in the field of irradiation, in connection with the changing parameters and operating conditions. The use of high-purity metals as initial components of new structural materials and the development or optimization of their smelting technologies should ensure the required level of characteristics and properties of products made from them. The implementation of these concepts should be ensured by the development of new structural materials: ferritic-martensitic and austenitic steels, nickel and other new alloys.

Key words: construction materials, active zone, nuclear reactor.

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КОНСТРУКЦІЙНІ МАТЕРІАЛИ АКТИВНИХ ЗОН ЯДЕРНИХ РЕАКТОРІВ НОВОГО ПОКОЛІННЯ

У матеріалах статті розглядається аналіз конструкційних матеріалів активних зон ядерних реакторів нового покоління. Аналіз відображає загальні уявлення про розвиток реакторних технологій: у 1950-60-х роках було створено перше покоління реакторів; на початку 1970-х років почалася експлуатація промислових реакторів - реакторів другого покоління: реактори з водою під тиском (ВВЕР, PWR), реактори з киплячою водою (РБМК, BWR), важководні реактори (CANDU), а також реактори з газовим охолодженням (AGR). Подальший розвиток деяких типів реакторів дозволив у 1980-х роках створити реактори третього покоління. Пріоритет при виборі напрямків розвитку в категорії революційних проектів повинні мати пропозиції, здатні внести нову якість у вирішення проблем атомної енергетики майбутнього. Перспективні реактори мають переваги в економічності, безпеці, надійності та нерозповсюдженні ядерних матеріалів. Ефективність і надійність конструкційних матеріалів визначаються сукупністю змін характеристик матеріалів в результаті всього комплексу явищ, що відбуваються в них в області опромінення, у зв’язку з параметрами, що змінюються, і умовами експлуатації. Використання металів високої чистоти як вихідних компонентів нових конструкційних матеріалів і розробка або оптимізація технологій їх виплавки повинні забезпечити необхідний рівень характеристик і властивостей виробів з них. Реалізація цих концепцій має бути забезпечена розробкою нових конструкційних матеріалів: феритно-мартенситних і аустенітних сталей, нікелю та інших нових сплавів.

Ключові слова: конструкційні матеріали, активна зона, ядерний реактор.

Introduction

The further development of nuclear energy is connected with the development of the following directions: improvement of the nuclear fuel cycle with the minimization of radioactive waste; economical use of uranium resources; reducing the risk of proliferation of nuclear materials; economic competitiveness with other energy sources; safety of operation of nuclear facilities; generation of promising nuclear energy technologies.

When developing nuclear power plants of the new generation, the task is not only to maximize the nuclear safety of reactors and improve economic indicators, but also to increase their environmental safety due to the use of structural materials of active zone elements with a relatively rapid decline in activity (achieving an affordable level of γ-radiation within 50…100 years after the shutdown of the reactor). Therefore, structural materials should not only be heat-resistant, thermocyclically strong, radiation-resistant, but also satisfy the requirement of low activation or rapid decline of the given activity. The use of low-activated steel for the manufacture of the reactor housing and internal equipment allows for a 5-fold reduction in the dose load on service personnel and a 20-fold reduction in the characteristic decay time of the given activity compared to the materials already in use.

For nuclear reactors with fast coolants, there are many requirements (temperature, pressure, neutron spectrum) that are reflected in the selection of similar materials or classes of materials for different types of reactors [1].

The aim of the work

Analysis of operating conditions and main characteristics of promising nuclear power plants, which involves the maximum increase in the efficiency of power plants and the transition to increasingly high operating temperatures, which in turn leads to the development of new structural materials. The materials of promising nuclear power plants must meet the unique requirements dictated by the design of high-temperature systems, which involves taking into account the influence of radiation, coolant, as well as static and dynamic stresses.

The general part

The further development of nuclear energy is connected with the development of the following directions: improvement of the nuclear fuel cycle with the minimization of radioactive waste; economical use of uranium resources; reducing the risk of proliferation of nuclear materials; economic competitiveness with other energy sources; safety of operation of nuclear facilities; generation of promising nuclear energy technologies.

Anticipating the large-scale development of nuclear energy and its implementation in various areas of energy production, it is necessary to work on nuclear reactors of a new generation that best meet these tasks. There is no doubt that for the next one and a half dozen years, the projects of the reactors under construction will make maximum use of technical solutions, types of equipment that have already been confirmed during operation, or are their improved continuation.

In the 1950s and 1960s, a number of prototype and demonstration reactors were selected, built and put into operation from many proposed reactors, differing in a wide range of coolants, nuclear fuels and designs. They made up the first generation of reactors. In the early 1970s, the operation of commercial reactors ─ reactors of the 2nd generation: pressurized water reactors (PWR), boiling water reactors (BWR), heavy water reactors (CANDU), as well as gas-cooled reactors (AGR). Further development of some types of reactors made it possible to develop third-generation reactors in the 1980s: improved BWRs and PWRs. Generation III+ is the next phase in the development of nuclear power plants, which includes evolutionary conceptual designs of water-cooled light water reactors that provide increased cost-effectiveness. According to experts' forecasts, the construction and commissioning of new capacities by 2030 will take place at the expense of generation III+ systems [2].

However, evolutionary projects may not provide a complete solution to the problems of nuclear energy in the future. Therefore, research and development of revolutionary projects of reactors of the next generations, which would provide solutions to the problems of large-scale energy, are necessary. Proposals that can bring a new quality to solving the problems of the nuclear energy industry of the future should have priority when choosing areas of development in the category of revolutionary projects.

The international community for the generation of new energy technologies has marked the list of reliable reactor systems and concepts of the next IV generation after 2030 (International Forum ─ Generation IV (GIF), the IAEA project on innovative nuclear reactors and fuel cycles (INPRO) and a number of other projects) [2] – [6]. This list includes: reactors cooled by lead alloys (LFR); liquid salt reactors (MSR); sodium liquid cooled reactors (SFR); supercritical water-cooled reactors (SCWR) (25°MPa, 280 °C…580 °C); high-temperature gas-cooled reactors (HTGR); particle accelerator-driven subcritical assembly systems (ADS). The most common ideas that can be found in conceptual projects in various combinations are:

1) The temperature at the exit from the reactor is much higher than in modern reactors – 600 °C…1200 °C. Thanks to this, it is possible to generate hydrogen, environmentally friendly fuel in thermochemical and electrochemical cycles.

2) Accelerator Driven Systems (ADS) are the most likely candidates for G-IV. Subcritical reactors, with a neutron reproduction coefficient $k \approx 98$ %, can be successfully used with external neutron sources of the accelerating type. The necessary 2 % of neutrons will be generated by beams of protons (or electrons) on a metal target. Uranium, tungsten and other materials are being considered as possible target candidates.

3) Metal melts (Pb, Pb-Bi eutectic (PBE), Na) are suitable as attractive heat carriers. In contrast to gas coolants (for example, He), metal melts work effectively at low pressure. Pb and PBE are particularly interesting because they are not as chemically aggressive as Na in case of leakage.

4) Liquid fuel in the form of molten salts of metal fluorides is considered as a promising unconventional fuel in some projects. The use of liquid fuel simplifies the fuel cycle, its preparation and processing.

Promising reactors have advantages in economy, safety, reliability and non-proliferation of nuclear materials. The temperature of the active zones of these systems is 600 °C…1200 °C, and the energy spectrum of neutrons is fast and in some cases thermal. The implementation of these concepts should be ensured by the development of new structural materials: ferritic-martensitic and austenitic steels, nickel and other new alloys.

The workability and reliability of structural materials are determined by the set of changes in the characteristics of the materials as a result of the entire complex of phenomena occurring in them in the field of irradiation in relation to the parameters that change and the operating conditions of the reactor [1], [7].

The interaction of the characteristics of the materials on each other when working in the reactor is so great that most often, in special experiments, their exact values cannot be determined and their influence on the performance of the fuel is judged qualitatively by the final practical result.

An analysis of the operating conditions and main characteristics of promising nuclear power plants shows that the desire to maximize the efficiency of power plants involves a transition to increasingly high operating temperatures, which in turn leads to the development of new structural materials. The materials of promising nuclear power plants must meet the unique requirements dictated by the design of high-temperature systems, which involves taking into account the influence of radiation, the coolant, as well as static and dynamic stresses.

For nuclear reactors with different coolants, there are many requirements (temperature, pressure, neutron spectrum), which is reflected in the choice of similar materials or classes of materials for different types of reactors.

When developing nuclear power plants of the new generation, the task is not only to maximize the nuclear safety of reactors and improve economic indicators, but also to increase their environmental safety due to the use of structural materials of active zone elements with a relatively rapid decline in activity (achieving an affordable level of radiation within 50…100 years after the shutdown of the reactor). Therefore, structural materials should not only be heat-resistant, thermocyclically strong, radiation-resistant, but also satisfy the requirement of low activation or rapid decline of the given activity. The use of low-activated steel for the manufacture of the reactor housing and internal equipment allows for a 5-fold reduction in the dose load on service personnel and a 20-fold reduction in the characteristic decay time of the given activity compared to materials already in use [1].

It is known that the indicated activity of alloys depends on the level of impurities in steels, as well as the presence of alloying elements that make a large contribution to the value of the indicated activity. Thus, if possible, alloys should not contain or contain in limited quantities such elements as niobium, molybdenum, nickel, copper, silver, cobalt, etc. Therefore, these elements must be excluded or replaced by others, for example, Mo by W; Nb on Ta, V, Ti, in addition, it is necessary to limit the content of Ni and impurities activated by Co, Cu, Ag, etc. [1], [7] – [9].

The high level of content of impurity elements and gases in steels and alloys significantly reduces their mechanical, corrosion and radiation properties, and therefore limits their use in operating reactors and in reactors being designed. Irradiation of 16X12V2FTaR steel causes the formation of gaseous transmutants (H and He) and low-melting metals (Li, Mg, Zn, Cd, Ca, and possibly others) in its composition, the concentration of which increases with increasing exposure time, depends on the content of alloying elements and can amount (after 10 years of irradiation) to the amount of ~0.1 mass%. [1].

From the calculated data of the indicated activity and the time dependences of the decline of the indicated activity after irradiation of alloys of the V-Ti-Cr system in the neutron spectra of fission and synthesis (full neutron dose $5 \cdot 10^{27}$ m^2), it follows that the level of impurity content reached today increases the time to reach the level of residual activity 10^{-2} Zv/h (the remote level at which the processing of such materials is allowed) is approximately ten times compared to alloys without impurities [10].

Conclusions

The use of high-purity metals as initial components of new structural materials and the development or optimization of their smelting technologies should ensure the required level of characteristics and properties of products made from them.

Promising reactors have advantages in economy, safety, reliability and non-proliferation of nuclear materials. The temperature of the active zones of these systems is 600 °C…1200 °C, and the energy spectrum of neutrons is fast and in some cases thermal. The implementation of these concepts should be ensured by the development of new structural materials: ferritic-martensitic and austenitic steels, nickel and other new alloys.

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